## **Navigating Large Virtual Spaces**

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## **CONTENTS**

EXECUTIVE SUMMARY E-
INTRODUCTION
BACKGROUND1
Spatial Knowledge
THE DEVELOPMENT OF VIRTUAL WORLD DESIGN PRINCIPLES TO ENHANCE WAYFINDING ABILITY
Organizational Principles       3         Map Design Principles       4
METHOD
Subjects.5Virtual Environment Design5Apparatus7Design.7Procedure8
RESULTS AND DISCUSSION
Primed Search Time8Naive Search Time9Ratio of Percent of Area Searched to Total Time10Map Distance Error12Map Direction Error13Land Map Error14Search Strategies and Behaviors15
CONCLUSIONS
ACKNOWLEDGEMENTS
PEEERENCES 10

## **EXECUTIVE SUMMARY**

#### INTRODUCTION

As important as navigation is to human performance in virtual worlds, support for effective navigation is often overlooked in the design process. This document reports an experiment intended to show that real-world wayfinding and environmental design principles are effective in designing virtual worlds which support skilled wayfinding behavior. The design principles are adapted from both the cognitive psychology literature and urban and architectural design methodologies. There are two categories of design principles; those that guide the organizational structure of the environment, and those that guide the use and presentation of maps.

The study measures subject performance on a complex searching task in a number of virtual worlds with differing environmental cues. The environments are extremely large and consist of open sea, land, and ships which are used as targets for search tasks. The worlds are augmented with either a radial grid, a map, both, or neither. For each trial, the subject's viewpoint position and orientation was sampled approximately once per second. A verbal protocol with accompanying video was used to elicit information about the search strategies employed. A map drawing exercise followed each trial in order to gain insight to the subject's spatial knowledge (i.e. cognitive map) of the environment.

#### RESULTS

The results show that subjects in the treatment without any additional cues were often disoriented and had extreme difficulty completing the task. The grid was shown to provide superior directional information but both treatments using the map were superior overall due to the geocentric perspective provided. Behaviors associated with each treatment indicate that the cues had a strong effect on both search performance and search strategy. The results suggest that users of large-scale virtual worlds require structure in order to effectively navigate. Augmentations such as direction indicators, maps, and path restriction can all greatly improve both wayfinding performance and overall user satisfaction.

#### INTRODUCTION

From Christopher Columbus to the space shuttle, navigation has long been an important and vital concern for explorers of our world. This is equally true of explorers of virtual worlds; especially large worlds that can not be viewed from a single vantage point and consequently, require extensive movement to navigate. In fact, problems associated with wayfinding and navigation are predictably encountered in every large virtual world. Navigators of these worlds often become disoriented and are unable to perform the simplest of searching tasks. Compounding the problem is the fact that many virtual worlds are rarely, if ever, revisited offering the navigator limited opportunity to develop a usable cognitive map of the environment.

As important as these issues are to human performance in virtual environments and the eventual acceptance of virtual environment solutions to real problems, there currently exists only ad hoc remedies and case studies to which we can refer for guidance. The overall objective of our research program is to develop design principles that can be incorporated into a methodology for the design of wayfinding augmentations to virtual worlds. The implementation of these principles is expected to facilitate expert-like navigation performance in novice users. This research presents the first major steps towards our goal. We will show that real-world wayfinding and environmental design principles are effective in designing virtual worlds that support skilled wayfinding behavior (i.e. purposeful, oriented movement during navigation). This document reports an experiment to investigate this hypothesis.

#### **BACKGROUND**

The principles we investigate in this paper are based on spatial knowledge theory and environmental design methodology. Our objective is not to find new principles that are unique to virtual worlds, but rather to show that much of what is already known about wayfinding in the physical world is independent of the type of space and, therefore, can be applied to computer-generated environments. This study is the first of its kind leading toward a generalized design methodology for building navigable virtual worlds.

## Spatial Knowledge

In general, wayfinding performance improves with increased spatial knowledge of the environment. This knowledge has been described in terms of three hierarchical levels of information (Thorndyke & Goldin, 1983; Thorndyke & Hayes-Roth, 1982; Thorndyke & Stasz, 1980).

- 1. **Landmark knowledge** is information about the visual details of specific locations in the environment. It is memory for notable perceptual features such as a unique building.
- 2. **Procedural knowledge** (also known as route knowledge) is information about the sequence of actions required to follow a particular route. Procedural knowledge is built by connecting isolated bits of landmark knowledge into larger, more complex structures.
- 3. **Survey knowledge** is configural or topological information. Object locations and inter-object distances are encoded in terms of a geocentric, fixed, frame of reference. A geocentric frame of reference is a global, map-like view while an egocentric frame of reference is a first-person, ground-view relative to the observer. Survey knowledge has been found to be essential for skillful way-finding (Lynch, 1960).

In its advanced stages of development, procedural knowledge becomes survey knowledge, enabling inferences to be made from a geocentric perspective. Alternatively, survey knowledge can be obtained directly from maps. However, if acquired by this method survey knowledge tends to be orientation-specific

requiring that the navigator conceptually rotate the mental representation of the space to match the environment.

The resulting inflexibility of spatial knowledge acquisition, whether landmark, procedural or survey, associated with map learning led Levine to explore what effects this phenomenon has on map design (Levine, Jankovic & Palij, 1982; Levine, Marchon & Hanley, 1984). Levine draws three conclusions from these experiments which are the basis of map design theory.

- The *two-point theorem* states that a map reader must be able to relate two points on the map to their corresponding two points in the environment.
- The *alignment principle* states that the map should be aligned with the terrain. A line between any two points in space should be parallel to the line between those two points on the map.
- The *forward-up principle* states that the upward direction on a map (assuming it is mounted perpendicular to the floor) must always show what is in front of the viewer.

The primary issue in map design theory is that the map be congruent with the environment. This allows the viewer to quickly identify his current position and orientation on the map and consequently, in the environment. Although map use is not an appropriate tool for every situation, the ability to quickly extract survey knowledge directly from a map often makes it a powerful navigation aid.

Even when spatial knowledge is well developed and functional, it still has a tendency to be error prone. Distortions often occur due to the hierarchical nature in which spatial information is encoded (Stevens & Coupe, 1978). We do not tend to represent the relative positions between all places we encounter. Large regions, such as continents, encompass smaller regions, such as countries, and so on until the lowest level of detail has been encoded. Errors occur when direction is inferred from a high level of abstraction. For example, Reno, Nevada is actually farther west than San Diego, California. Yet this is often estimated in error due to the encoding of California as being west of Nevada.

## **Environmental Design**

Spatial knowledge theory is well represented in environmental design methodology. Urban planners and architects have long been interested in designing spaces that are easily navigable and, consequently, pleasant places to be. Lynch (1960) describes the urban setting in terms of what he calls urban design elements. These include:

- *Paths* are channels of movement. They include walkways, streets, railroads, expressways, and mass transit lines. These are typically the perspective from which an observer views the city.
- *Edges* are linear, not unlike paths, but do not facilitate movement. They are often boundaries defining a break in continuity between two homogeneous regions. Examples include shores, walls, rivers, and railroads cuts.
- *Districts* are the mid-sized sections of a city. They are distinguishable as having some common, identifying characteristics. Typical identifying traits include a particular architectural style, light posts, or mailboxes.
- *Nodes* are strategic spots in the city where observers can enter. They are typically linked to travel and may be represented by some type of transportation hub such as a mass transit station, bus stop, or traffic circle.

• Landmarks are point-references that are external to the observer. They are not entered into but rather are viewed from a distance. A landmark must be distinct from its surroundings and should have directional information associated with it. Directional information is essential to the navigator's ability to remain oriented with the environment.

Landmarks, nodes, and districts divide the city into "places"\* which are connected by paths and bounded by edges. Passini (1984) extends this model to architectural design adding that a space should have a basic organizational principle. For example, Manhattan is organized by a grid structure. A New York City traveler, knowledgable of this fact, will use this information to guide movement.

# THE DEVELOPMENT OF VIRTUAL WORLD DESIGN PRINCIPLES TO ENHANCE WAYFINDING ABILITY

This study is an extension of our initial study of navigation aids that investigated behaviors associated with specific stimuli (Darken & Sibert, 1993). The purpose of this study was to show that spatial knowledge theories and environmental design principles are applicable to the design of virtual worlds.

## **Organizational Principles**

The application of environmental design principles is suggested to provide the necessary structure by which an observer can mentally organize a virtual environment into a spatial hierarchy capable of supporting wayfinding tasks. Organizational principles intended to achieve this goal are:

- 1. Divide the large world into distinct small parts, preserving a sense of "place". This division should be hierarchical in nature.
- 2. Organize the small parts under a simple organizational principle, such as a grid or logical spatial ordering (e.g. a street naming convention).

Orientation is very critical to effective wayfinding. The wayfinder must always be properly oriented with the space. If disoriented, new spatial knowledge may be encoded erroneously and existing spatial knowledge may be difficult or impossible to apply to wayfinding problems. Directional cues can prevent or minimize such disorientation. Therefore, a third principle is included:

3. Provide frequent directional cues. This information can be supplied in the form of directional land-marks or independently, as in a compass.

<sup>\*.</sup> A "place" is a unique location or region of space which is easily recognizable to the observer.

## **Map Design Principles**

The importance of maps to spatial knowledge acquisition cannot be overlooked. Ideally, this knowledge should be flexible, as if the observer had obtained it directly from experience. However, navigators of virtual worlds are often not given enough exposure to any one world to develop this form of knowledge. The provision of a virtual map is intended to present spatial information in such a way as to produce a flexible, orientation-independent representation of the virtual environment. Thus, the flexible spatial knowledge acquired from a virtual map should enhance wayfinding performance. The virtual map should be designed according to the following principles derived from map design theory:

- 1. Show organizational elements (paths, landmarks, districts, etc.) and particularly the organizational principle(s).
- 2. Always show the observer's position so that the two-point principle can be accommodated.
- 3. Orient the map with respect to the terrain and observer such that the alignment and forward-up equivalence principles are accommodated.

Note that the two latter principles are difficult to apply in the real world when the observer is moving. In the virtual world, however, they can be applied equally easily to a stationary or moving observer.

These six wayfinding design principles provide the foundation from which to design navigable virtual environments. The purpose of this study was to apply these six principles to several virtual environments and evaluate their effect on wayfinding performance. The environments used to validate these principles were simple, physically-similar worlds. Beginning with a simple, familiar type of space, subjects were expected to be better able to focus on the experimental task itself rather than on understanding the unusual attributes of a more complex space.

The form of the task was also an issue. In order to consider the primary relevant wayfinding tasks, the following question was posed: "When you move, why are you moving?". Assuming that only primary task-related, purposeful movement takes place, there are two broad classifications of possible tasks: searching and exploring. This is extended to include:

- Naive search: Any searching task in which the navigator has no a priori knowledge of the whereabouts of the target in question. A naive search implies that an exhaustive search is to be performed.
- **Primed search**: Any searching task in which the navigator knows the location of the target. The search is non-exhaustive.
- **Exploration**: Any wayfinding task in which there is no target.

Although these categories are mutually exclusive, wayfinding tasks are commonly combined hierarchically to form compound tasks. Primed searches to general areas can be followed by naive searches of that area and vice versa. (see Figure 1).

#### **METHOD**

The proposed design principles were investigated by measuring performance on wayfinding tasks in several virtual world treatments each of which provided a different form of assistance. Some treatments adhered to a subset of the wayfinding principles; others did not. The four treatments used in the experiment were:

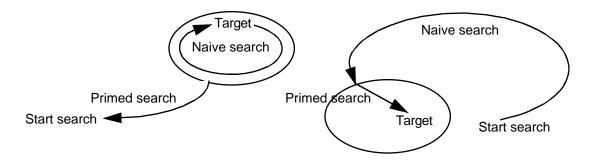


Fig. 1 — The hierarchical nature of compound wayfinding tasks

- The Control Treatment: No wayfinding assistance provided
- The Grid Treatment: Adherence to organizational principles
- The Map Treatment: Adherence to map principles
- The Map/Grid Treatment: Adherence to both organizational and map principles

## **Subjects**

The experiment used a repeated measures design. Ten subjects participated in this study (five males and five females). The availability of subjects was limited due to both the location of the laboratory and the total time required to complete all trials (approximately three hours for each subject). All subjects had a technical background and were between the ages of 20 and 45 ( $\bar{x} = 29.5$ , s = 5.7). Experience with the actual apparatus or similar devices was not required.

## **Virtual Environment Design**

There were five environments built for this experiment. The physical composition of each environment was similar, consisting of only land masses, open sea, and target objects (ships). In addition, each environment was exactly the same shape and size - 12,000 square kilometers in real-world dimensions. The worlds used in this experiment were not actual terrain data but were constructed by hand using a geometric modeling tool. The land masses were colored by elevation and the ocean surface was textured with a sea texture that was scaled to hide the repetition of its pattern. The land masses were shaped and scaled to be distinct from one another. However, no attempt was made to provide any sort of natural landmark which could be used for navigation such as mountains, valleys, or other unusual landforms. The ability of subjects to infer the topographical structure of the worlds was partly at issue in the experiment. The targets were manually placed in the worlds, each with a random orientation. A numbered cube above each target uniquely identified it. The worlds were constructed so that a large buffer of open ocean surrounded the land masses on all four sides. This was done to minimize the ability of the subject to use the "edge" of the world as a navigation aid.

The viewpoint was restricted to movement above the terrain but below the maximum altitude of 400 meters. This is necessary to allow some vertical movement without allowing the subject to gain enough altitude to be able to look down on the entire environment from a "bird's eye view" which has been shown to be a navigational aid (Darken & Sibert, 1993) Movement was constrained horizontally so that when the subject reached the furthest extent of the world, there would be no distinguishable features by which to navigate. Contact with the virtual edge resulted in an audible "click" cue combined with the immediate halt of the view at the point of contact.

For the grid treatment, a radial grid (see Figure 2) was designed according to the organizational principles. First, it was designed around a radial grid structure according to principle 2. Second, according to principle 1, the grid divided the environment into distinct sections which were marked by color. The grid was constructed from a red center post, which did not indicate direction, and four color posts in each cardinal direction. The outer posts each had a "flag" that pointed inward toward the red inner post (principle 3). There were three concentric rings marking the range. The red, yellow, and white rings were placed at 10000m, 20000m, and 40000m radius respectively. The outer posts were placed on the white ring. Black radial lines were placed every 45 degrees and extended beyond the white ring.

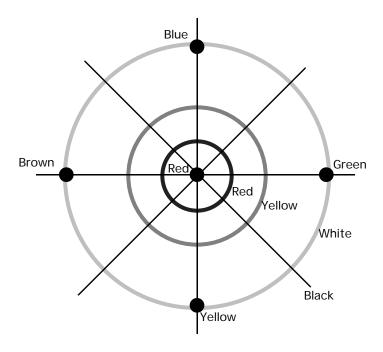


Fig. 2 — The radial grid

For the map treatment, a map was designed according to the map design principles. The map was identical to the actual environment except that the blue sea texture was replaced by a gray background for contrast with the actual environment. A red sphere was moved along the map surface to identify the viewpoint position (principle 2). Rather than draw the map in an upright position, the map was presented flat and in the same orientation as the environment itself (principle 3). The map was placed relative to the viewpoint during movement making it visible at all times. The intent was for subjects to feel that the map was in front of their chest.

For the map/grid treatment, the grid was placed over the map and the world simultaneously (map design principle 1). The map/grid treatment is shown in Figure 3. Notice the numbered cube identifying the object as target zero (the home target) and the orientation of the map relative to the environment.

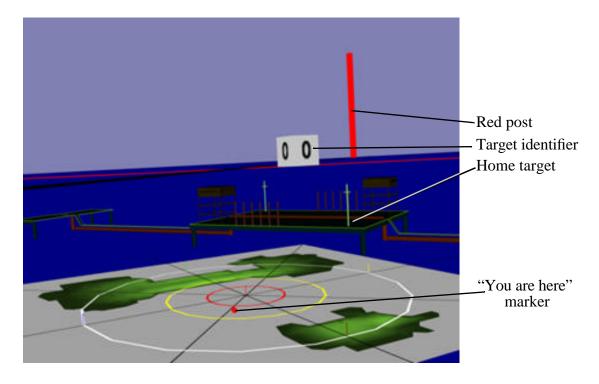


Fig. 3 — The map/grid treatment

## **Apparatus**

The computing hardware and graphics engine used was a Silicon Graphics Onyx<sup>TM</sup> Reality Engine 2<sup>TM</sup> workstation. The only peripheral device used was a Fakespace Inc. BOOM3C<sup>TM</sup> display and tracker. The BOOM3C<sup>TM</sup> is a full color, high resolution (1280x1024 pixels), CRT-based display mounted on a counter-balanced mechanical arm. The display is held to the eyes with one hand which controls a single button and an eight position thumb-operated joystick. Only the up and down positions of the joystick are used. The position and orientation of the head are tracked through the mechanical arm. Motion is controlled via an acceleration metaphor by which the subject accelerates forward in the virtual world by pushing up on the joystick and backward by pulling down. Velocity is bounded by a speed limit approximately equal to Mach 3 (993 m/s or 2223 mph). Movement is *always* in the direction of view. The subject may stop at any time by pushing the red thumb button. Orientation cannot be altered with the buttons or joystick.

## Design

A Friedman two-way within-subject ANOVA was used to analyze the results. This is a nonparametric test of interval data suitable for experiments with small subject sample sizes. The sequencing of the four treatments was randomized among subjects. However, a training session on a separate environment under control conditions preceded the four treatments. This was done to familiarize subjects with the apparatus and the experimental procedure in such a way as to limit presentation order effects on the data. Dependent variables included: search time; ratio of percent of area searched to total time; map distance error; map direction error; land map errors; and search strategies and behaviors. The effects of changes in the stimuli (environmental cues) were expected to be observed in the response behavior (wayfinding task perfor-

mance), as well as in both the cognitive map and search strategies. The cognitive map was evaluated using a map drawing exercise to elicit information about the subject's mental representation of the world used in each treatment (Howard & Kerst, 1981; Lynch, 1960). Performance was measured with execution timings and viewpoint position and orientation sampling (approximately once per second). Search strategies and behaviors were analyzed from a verbal protocol analysis with video (Bainbridge, 1991; Byrne, 1983).

#### **Procedure**

The wayfinding task performed for all treatments required the subject to execute five naive searches followed by one primed search. The subject started at the home target and proceeded to search the environment for each of the five ships that were numbered and shown to the subject in written instructions. No a priori information was given as to their whereabouts. Once the last target had been located, the subject was required to return to the home target. Subjects were given as much time as needed to complete the task. However, the trial could be discontinued at the subject's request. This was allowed only in cases when either the subject felt unable to make any progress toward task completion after an extended period of time (always at least 15 minutes) or the subject became unable to continue for physical reasons\*.

During task execution, subjects were asked to "think aloud" (Byrne, 1983) as a method of knowledge elicitation specifically aimed at understanding search strategies. At no time were subjects assisted in the performance of the wayfinding task. Following each trial, subjects were required to draw a map of the environment in as much detail as possible. Subjects were free to sketch the environment at will starting from a blank piece of paper. This method allowed subjects some artistic freedom to sketch what they deemed as "important" environmental features.

#### RESULTS AND DISCUSSION

The analysis is presented in two parts; first the quantitative results are presented and then the qualitative results are reviewed.

#### **Primed Search Time**

The actual primed search time was defined as the total time beginning immediately after the last naive search and ending with the relocation of the home target. If the primed search was unsuccessful (four subjects in the control treatment; none in the other treatments), the time is replaced with the greatest time of any *successful* primed search across subjects for that treatment.

A low primed search time indicates a proficient primed search with little wasted movement. These searches require a highly functional and accurate mental representation of the space and, as important, knowledge of a route to the home target or a method for its relocation.

The differences in primed search were found to be significant across treatments (Friedman test statistic = 13.56,  $\underline{p}$  0.005). The order of presentation was found to be insignificant ( $\underline{F}(3,24) = 0.101$ ,  $\underline{p} = 0.958$ ). There was also no significant difference due to gender within any treatment (Control,  $\underline{F}(1,8) = 0.001$ ,  $\underline{p} = 0.976$ ; Map,  $\underline{F}(1,8) = 0.645$ ,  $\underline{p} = 0.445$ ; Grid,  $\underline{F}(1,8) = 0.630$ ,  $\underline{p} = 0.450$ , Map/Grid,  $\underline{F}(1,8) = 0.073$ ,  $\underline{p} = 0.794$ ). The data are shown in Figure 4. The individual times for each treatment within each subject are shown vertically. The averages across subjects are shown in the last column and are extended across the chart with dashed lines.

<sup>\*.</sup> There were two cases of motion sickness.

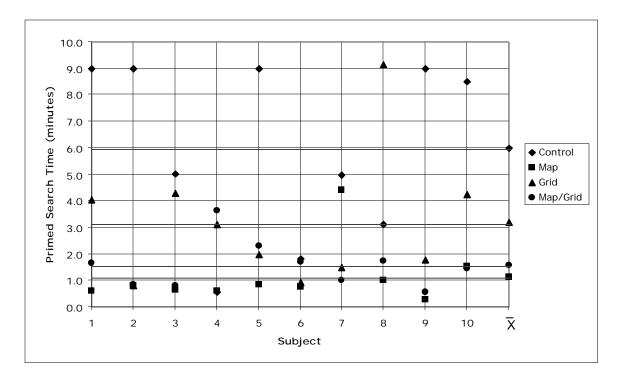


Fig. 4 — Primed search time

The three minute separation between the control treatment average and the other conditions may indicate that most subjects were unable to direct their search in an effective manner without navigational cues. In fact, disorientation often caused the primed search in the control treatment to be no different from the naive searches (i.e. another exhaustive search was performed). Although the primed search in the grid treatment is higher than the map treatments, the difference from the control average shows that subjects were able to maintain their orientation allowing them to either infer the direction of the home target or to construct a reasonable plan by which to return there. The geocentric point of view provided by the map treatments eliminates the necessity of inferred direction allowing direct access to a path to the home target and consequently, trivializes this subtask.

## **Naive Search Time**

For this factor, all incomplete search times are adjusted, then each of the five naive search times are averaged. In those cases where the subject did not successfully complete one or more of the searches (three subjects in the control and grid treatments; two in the map/grid treatment; one in the map treatment), the time is adjusted by replacing it with the greatest time of any *successful* naive search across subjects for that treatment. Naive search time is related to the subject's ability to conduct an organized exhaustive search. A high average naive search time indicates probable disorientation and multiple path traversal.

The differences in average naive search times across treatments were not found to be significant (Friedman test statistic = 6.84, p = 0.077) (see Figure 5). The order of presentation was also found to be insignificant ( $\underline{F}(3,24) = 1.765$ , p = 0.181) and there was no significant difference detected due to gender within any treatment (Control,  $\underline{F}(1,8) = 4.015$ ,  $\underline{p} = 0.080$ ; Map,  $\underline{F}(1,8) = 1.318$ ,  $\underline{p} = 0.284$ ; Grid,  $\underline{F}(1,8) = 3.112$ ,  $\underline{p} = 0.115$ , Map/Grid,  $\underline{F}(1,8) = 1.086$ ,  $\underline{p} = 0.328$ ).

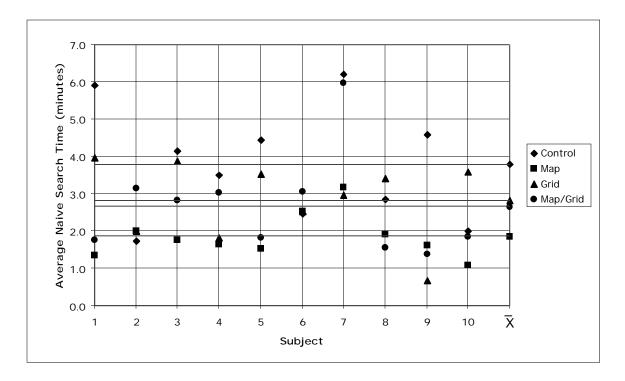


Fig. 5 — Naive search time

The control treatment remains the most time-consuming treatment for search tasks. The treatments are more tightly grouped primarily due to the actual search techniques employed. In the control treatment most subjects chose to search by following the coastlines. This often resulted in relatively rapid target location. However, subjects using this method were often disoriented with respect to the shape and extents of the environment resulting in relatively poorly drawn maps (See "Search Strategies and Behaviors"). This was not the case for the other three treatments. The differences between treatments are more evident here in a qualitative sense than quantitative.

## **Ratio of Percent of Area Searched to Total Time**

A measurement of the amount of environment actually searched during any trial is computed by placing a view volume "footprint" (the field of view and view depth are known quantities) at each of the sampled positions and orientations in the world. The composite image is then processed to determine what proportion lies outside of the covered region. In the example in Figure 6, the light grey region represents the searched area. This, combined with the land area, is subtracted from the whole resulting in a measure of searchable space (i.e. space in which a target could be found) which was not viewed. Total time is given as the sum of all five naive search times (actual and adjusted) and the primed search time. For this measure, the difference between treatments was found to be significant (Friedman test statistic = 13.80, p 0.005) (see Figure 7).

Those cases where large regions of space were searched in a relatively short amount of time (a high ratio on the graph) are more consistent with an intuitive definition of an efficient search. However, this measure tends to penalize those subjects who conducted an effective search which, undoubtedly with some

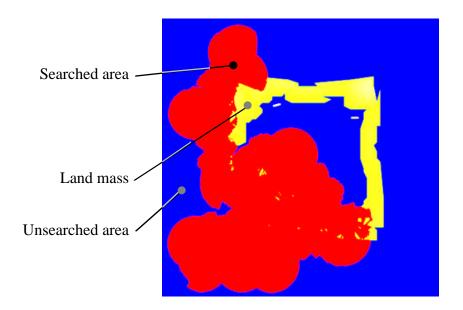


Fig. 6 — The percent of area searched metric

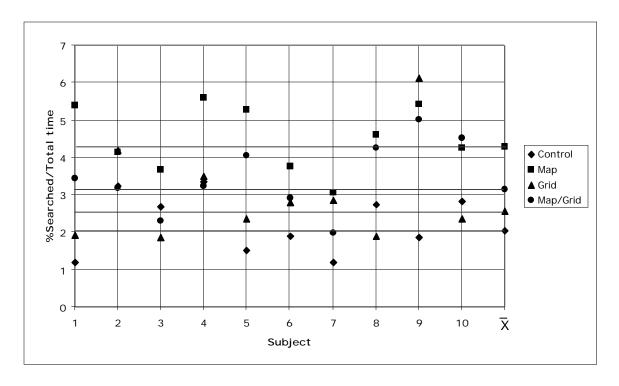


Fig. 7 — Percent of area searched to total time ratio

luck, located all targets without searching the entire environment and even more so, those subjects who happened to move relatively slowly.

## **Map Distance Error**

The next three sections deal with the evaluation of the maps drawn by each subject at the conclusion of every trial. Map distance and direction error were determined using a metric which normalizes results in order to make comparisons across subjects. The technique begins with measurements taken from an actual top-down view of each environment (see Figure 8A). The actual distances and relative bearings between all targets are measured. One direction (straight up in this example) is chosen to be bearing zero for all cases and all maps. Each map is evaluated similarly (see Figure 8B). A path is constructed from the home target to the last target identified and back to the home target. In this case the ordering is 0-2-3-5-1-4-0. The distance and relative bearing of each leg of this path (i.e. target to target) is compared to the actual values. The distances must be normalized by using the overall distance of the entire path as one. For example, the leg 0-2 is measured to be 6.1cm on the subject's map. The total path length is 34.4. Therefore the normalized 0-2 path length is  $6.1 \div 34.4$  or .177. These values are compared to those of the actual world resulting in the actual percentage error (.122 in this case).

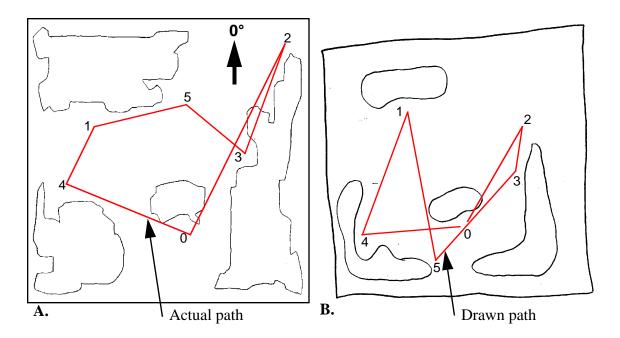


Fig. 8 — An example of the map distance and direction metric technique

The differences in map distance error were found to be insignificant (Friedman test statistic = 6.93, p = 0.074) (see Figure 9). The order of presentation was also found to be insignificant ( $\underline{F}(3,24) = 1.835$ ,  $\underline{p} = 0.168$ ) and there was no significant difference due to gender within any treatment (Control,  $\underline{F}(1,8) = 0.001$ ,  $\underline{p} = 0.977$ ; Map,  $\underline{F}(1,8) = 4.292$ ,  $\underline{p} = 0.072$ ; Grid,  $\underline{F}(1,8) = 2.840$ ,  $\underline{p} = 0.130$ ; Map/Grid,  $\underline{F}(1,8) = 0.041$ ,  $\underline{p} = 0.845$ ).

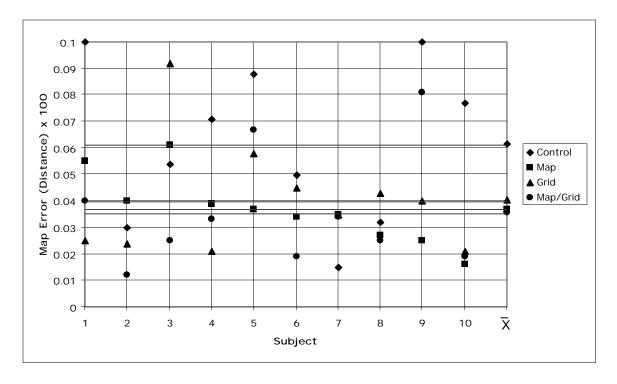


Fig. 9 — Distance map error

Studies of natural human ability to judge distance and direction show that distance estimation is typically easier and more accurate than direction estimation (Hale & Dittmar, 1994; Marshak, Kuperman, Ramsey & Wilson, 1987). This is supported by the data here in the direction errors (see Figure 10), which were an order of magnitude greater than distance errors (see Figure 9). For distance errors, the control treatment is separated from the other three treatments which are clustered tightly together. However, the separation is only a 2% difference. The variance is very high as there is no clear treatment in which distance estimation was significantly easier than another. Since overall distance error rates were low, it may be concluded that the cues for determining motion, specifically the sea terrain and the frame rate (optical flow), were effective in providing the necessary information to infer distance. However, the same cannot be said of direction.

#### **Map Direction Error**

Similar to the map distance error metric, map direction error was also measured in percent error from the original world. In the example of Figure 8, the relative bearing from target 0 to target 2 was measured to be  $35^{\circ}$  on the drawn map and  $28.6^{\circ}$  in the actual world. These can be compared directly. The maximum error was taken to be  $180^{\circ}$  which would place a target on the exact opposite side of its correct orientation. To normalize the data, the percent error was computed as the difference in measured angle divided by  $180^{\circ}$ . In this case,  $(35 - 28.6) \div 180 = .036$ .

The differences in map direction error were found to be significant (Friedman test statistic = 14.52, p 0.005) (see Figure 10). The order of presentation was found to be insignificant ( $\underline{F}(3,24) = 0.246$ ,  $\underline{p} = 0.863$ ) and there was no significant difference due to gender within any treatment (Control,  $\underline{F}(1,8) = 0.592$ ,  $\underline{p} = 0.464$ ; Map,  $\underline{F}(1,8) = 0.786$ ,  $\underline{p} = 0.401$ ; Grid,  $\underline{F}(1,8) = 0.762$ ,  $\underline{p} = 0.408$ ; Map/Grid,  $\underline{F}(1,8) = 0.012$ ,  $\underline{p} = 0.012$ ,

0.916). Again, the control treatment is separated from the other treatments by a large margin (nearly a 15% difference). This is expected considering that most subjects often appeared disoriented during the control treatment. What was not necessarily expected was the low error of the grid and map/grid treatments not shared by the map treatment. Clearly, the presence of the grid as an absolute orientation frame of reference affected the ability of subjects to place targets on the map. Furthermore, the extra attention given the grid during the grid treatment is evident in its overall superior error percentage. This is not true when the land masses are considered.

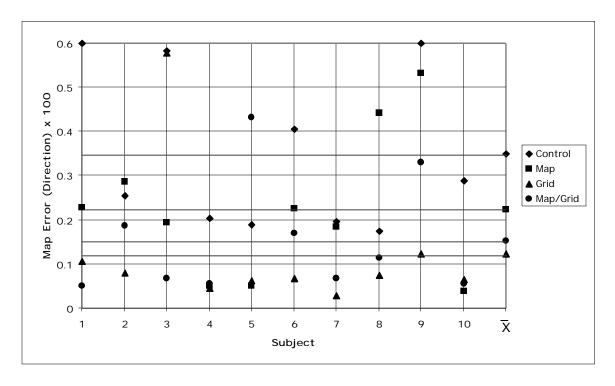


Fig. 10 — Direction map error

## **Land Map Error**

The previous two factors do not take into account the placement of land masses. As important as this factor is to the analysis, there are problems with defining a practical, yet descriptive metric for it. These difficulties resulted in the use of a subjective method for this analysis. This is a pattern matching problem. We want to know which maps show the land masses most similarly to the actual world. This includes the land mass shape, relative size, position, and orientation. Four geographers from Eastern Michigan University were given a copy of each of the maps grouped by world. They were asked to rate the maps in terms of their most salient features.

The resulting data is a rank ordering of the maps for each world which were then separated by treatment. The differences in land representation were found to be highly significant (Friedman test statistic = 18.84, p = 0.0001) (see Figure 11). The order of presentation was found to be insignificant ( $\underline{F}(3,24) = 0.345$ , p = 0.793) and there was no significant difference due to gender within any treatment (Control,

 $\underline{F}(1,8) = 5.448$ ,  $\underline{p} = 0.048$ ; Map,  $\underline{F}(1,8) = 0.478$ ,  $\underline{p} = 0.509$ ; Grid,  $\underline{F}(1,8) = 1.505$ ,  $\underline{p} = 0.255$ ; Map/Grid,  $\underline{F}(1,8) = 0.127$ ,  $\underline{p} = 0.730$ ).

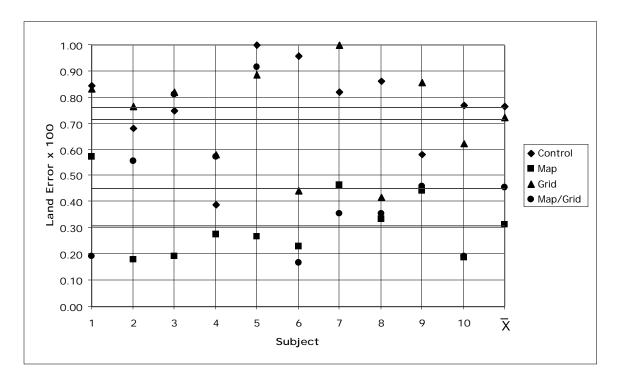


Fig. 11 — Map land error

As expected, the two map treatments which provided a geocentric view of the environment (i.e. map and map/grid) are clearly separated from the two egocentric treatments (i.e. control and grid). Targets are thought of as points which can be placed relative to the grid resulting in accurate map drawings. But the shape and size of land masses must be inferred in the egocentric treatments. Consequently, these features are more poorly represented in the grid treatment than in the map treatments.

## **Search Strategies and Behaviors**

The quantitative results presented thus far have shown strong evidence supporting the hypothesis that the presence of the wayfinding augmentations did significantly improve searching performance. In general, it has also been shown that the two map treatments have a stronger effect on performance than the grid treatment but that all three are significantly better than the control treatment. However, a qualitative analysis is required to describe the actual strategies used to perform the searches within each treatment. In this study, four basic search strategies were identified: edge, lawnmower, area, and heuristic.

The control treatment, being the most difficult and amorphous environment in which to navigate, exhibited widely varying search techniques. The most common of these was an *edge* following technique in which the subject primarily searches the boundaries of the land masses for targets. This technique often resulted in relatively time efficient searches but caused excessive disorientation. Subjects were unable to determine how far they had moved around the land and subsequently, did not maintain any static frame of

reference by which to orient their view. This is shown in Figure 12A where one subject's movement track is indicated by the dashed line. The targets have been enlarged many times for visibility at this scale. The path winds around each land mass with most edges being traversed more than once. The subject is clearly disoriented a number of times throughout this trial. This behavior is typical of this method. The corresponding map drawing (Figure 12B) shows that this subject was able to infer direction reasonably well. However, the land mass on the right side of the world has been placed much higher than it actually appears. The targets have been placed properly with respect to their nearest land mass but the land masses have not been placed correctly with respect to each other. The subject had no point of reference by which to make global position estimations.

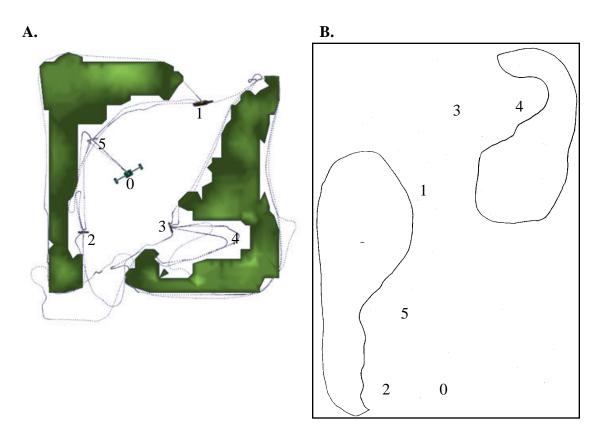


Fig. 12 — The edge following search method

Another subject in the control treatment used an external method of maintaining orientation. He grounded one foot relative to the physical world in order to have an absolute reference for reorientation. The search strategy he used involved finding a corner and then moving up and back across the world organizing the search into long parallel strips. The movement pattern is similar to that of a *lawnmower* (See Figure 13A). This method produced a much better map than the edge following technique. Both the land masses and targets are placed properly (See Figure 13B). This subject was oriented throughout the treatment and therefore did have a point of reference by which to make accurate direction and distance estimations.

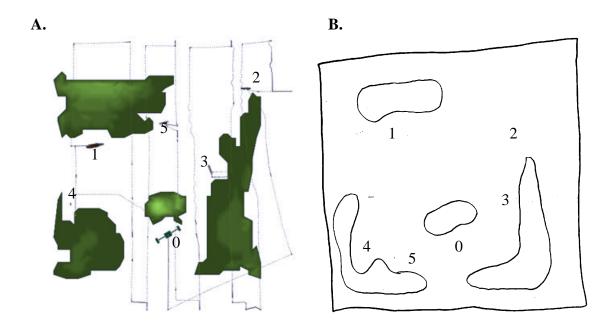


Fig. 13 — The lawnmower search method

When the map is used during navigation, the geocentric information provided allows a number of different search methods to be used. Most subjects again used the edge following method. This technique was found to be far more efficient in this treatment as subjects were able to determine how far they had travelled around each land mass. A derivative method used by some subjects involved using a *heuristic* to guide the edge following search. In the example of Figure 14A, a subject focused the search on land formations he thought most likely to contain a target. These areas are circled. The resulting map is also highly accurate (See Figure 14B). The orientation of the map provided the necessary grounding to allow accurate distance and direction estimates.

The presence of the grid in either the grid or the map/grid treatment had the most profound effects on searching patterns. The grid was purposely designed to be non-specific as to its use in navigation. It was used as a means of dividing the space into small parts, as an indicator of paths to be followed during search, and as direction markers indicating the cardinal directions. These uses were often combined and equally often, were ignored. The example in Figure 15A shows a subject in the grid treatment using an *area* search method. The world is divided into wedges with the rings indicating range from the center. The shape of the wedges as well as the outline of the yellow middle range ring are clearly evident. The corresponding map (See Figure 15B), while highly accurate in its placement of the targets, does not represent the land masses well. Judging from the path of the search, the reason is clear. The subject's movement path intersected each land mass many times from different directions providing no information as to how or if the land he was viewing was contiguous or disjointed. This method consequently rates highly in the map direction and distance metrics but relatively poorly in the land mass metric.

In summary, the edge following search strategy was the most common technique used across treatments. Although it often enabled task completion, it did not make use of an absolute frame of reference and, therefore, subjects were commonly disoriented. The lawnmower method used an external orientation source allowing a highly organized exhaustive search. However, this method required that a conceptual structure be applied to the environment which may be difficult to maintain. The area search method was

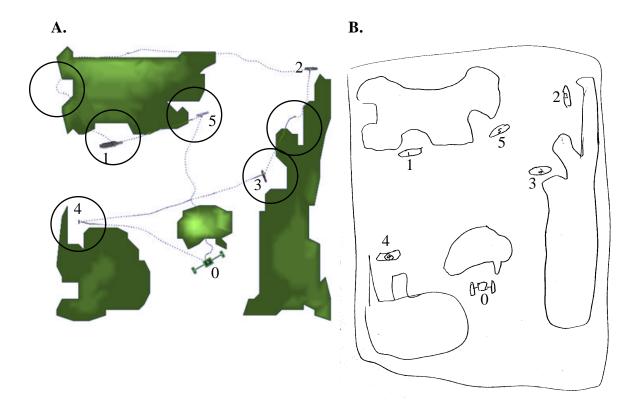


Fig. 14 — The heuristic search method

used only when the grid was present. This method was similar to the lawnmower method except that the structure was explicit rather than merely conceptual. The absolute frame of reference provided by the grid enabled highly accurate directional estimations. Lastly, a heuristic method was often used with the map to focus the search in specific areas of the environment. Short-cuts across the environment were possible due to the global view provided by the map.

#### **CONCLUSIONS**

The results showed that navigational performance was superior under both map treatments as compared to the control and grid conditions. The grid, however, was shown to provide superior directional information as compared to the other conditions. The control condition provided the worst performance, with subjects often becoming disoriented and experiencing extreme difficulty completing the tasks.

This work shows that real-world design principles, when extended to virtual worlds, support improved performance on navigation tasks. We focus attention on two primary areas; the organizational elements of environmental design, and map usage. Organizational elements serve to divide a large space into a number of smaller, connected parts. Additionally, directional information is added providing the navigator with an absolute frame of reference. Maps are used to show a geocentric perspective of the environment and the navigator's position in it.

The analysis of this experiment clearly shows a significant difference between the control treatment and the others. It is evident that the inclusion of something as simple as an absolute reference point will

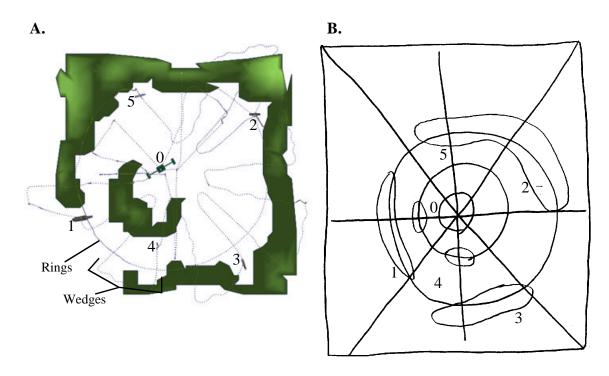


Fig. 15 — The area search method

improve navigation performance. A further investigation of the actual behaviors and strategies associated with the stimuli will strengthen our understanding of how environmental information is used for navigation. Although not all wayfinding augmentations are appropriate for every problem, this research begins to show what types of information are most important, how they can be provided, and how they might be used. This is the first major step toward a methodology for designing navigable virtual worlds.

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